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Economic security of regions: A methodological approach to assessment, management, and legal regulation

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Abstract. At the present stage of development, one of the major problems of regions is ensuring their economic security. This requires the development of effective methodological approaches to assess economic security at the regional level by governing bodies, and the development of directions for regulating economic security at the local and state levels. The purpose of the article is to form methodological tools for assessing the economic security of regions based on the method of fuzzy modeling, to develop approaches to managing the economic security of a region by public authorities and local governments. The article has proposed and analyzed indicators for assessing the economic security of regions. The scientific novelty of the article is the use of fuzzy modeling to assess the economic security of regions. This method, unlike others, allows you to use fuzzy input data in simulation modeling and obtain output data that can be reduced to crisp values using defuzzification methods. The expediency of using fuzzy logic tools to assess economic security at the meso-level has been substantiated. The effectiveness of the practical application of the proposed approach has been tested based on assessing the economic security of the regions in Ukraine. The integral index of economic security has been modelled, together with its components: investment, innovation, financial, foreign economic, demographic, social security, and security of economic activity. For the demonstration of the practical application of the proposed methodological approach, the data of 10 regions of Ukraine has been analyzed and their economic security has been assessed. The directions of economic and legal regulation of the analyzed regions of Ukraine, which are characterized by crisis and low level of economic security and its components, have been offered.

Key words: economic security, fuzzy logic, legal regulation, management, method of fuzzy modeling, region

1 Introduction

The main goal of managing the economic security of regions is the formation of favorable socio-economic and institutional conditions for the implementation of economic interests of each of their entities and the region, maintaining their functioning and intensive

development, ensuring their economic independence and freedom, competitiveness, and sustainable economic condition in the long run. Economic security management is aimed at timely detection and elimination of threats that arise in the economic system of a region and create unfavorable conditions for the development of socio-economic processes at the micro-, macro- and meso-levels of the national economy (Granberg et al. 2008, Varnaliy et al. 2016, Onyshchenko, Bondarevska 2018). All this, in turn, threatens the well-being of every individual, causes an increase in costs and a decrease in income from the economic activity of enterprises, leads to a reduction in production and sales of products, reduces investment demand, and restricts economic development (Yapatake et al. 2018, Arkhipova, Kulikova 2020, Tiutiunyk et al. 2017).

Furthermore, the management process is aimed at the development of preventive measures and measures to counteract the negative impact of destabilizing factors, at maintaining the sustainability of regions and economic entities under the conditions of uncertainty, and forming a legal framework for economic security of the regions. It is the timely application of effective management mechanisms which ensures prompt adaptation to negative changes, overcoming risks and threats, and manageability of the economic system of the region in the process of further development (Varnaliy et al. 2016, Grigoreva, Garifova 2015). That is why it is important to find the most optimal tools for managing the economic security of regions, as well as opportunities to promptly respond to negative changes in the internal and external environment through economic and administrative measures.

To solve this problem, it is necessary to form new methodological approaches to assess the economic security of regions, which would allow its objective quantitative and qualitative analysis. This will identify weaknesses and strengths of regions in investment, innovation, financial, foreign economic, demographic, social security, as well as economic security. Also, it is necessary to develop managerial measures to counter the risks and threats that arise in the economic system of a region, and on their basis to make more effective management decisions in the field of economic security of regions at the state and local government levels.

2 Literature

Issues of ensuring economic security at the regional level have been the subject of research by many economists. The theoretical foundations of the essence and forms of economic security were laid by representatives of the classical school of political economy and marginalism (Smith 1776, Ricardo 1817, Mill 1848, Pareto 1906, Varnaliy et al. 2016). Western scholars have mainly seen economic security as a component of national security or as a set of favorable economic and institutional conditions in society, which can provide protection from internal and external threats in the economic system, reduction of economic risks, and maintaining standards and quality of life (Luciani 1988, Cable 1995, Marsh 2012). Later, representatives of this school expanded their approach and studied the global aspects of economic security, as well as factors influencing national economic security, problems of regional economic security, and security of companies and individuals (Glaser 1997, Kahler 2004, Makštutis 2006, Rupert 2007, Hacker et al. 2014, Tamošiūnienė, Munteanu 2015, Nam et al. 2016, Koudoumakis et al. 2019).

In post-Soviet economic science, the problems of economic security at the macro-, micro- and meso-levels have been studied in more detail (Granberg et al. 2008, Varnaliy et al. 2016, Kharazishvili 2019, Arkhipova, Kulikova 2020, Grigoreva, Garifova 2015, Iefimova et al. 2020, Chistnikova et al. 2017, Ivanova et al. 2021).

Accordingly, in the process of scientific analysis, the scientists have formed current ideas about the economic security of regions. In particular, the scientists substantiated the theoretical aspects of economic security and its components, and identified the conditions that need to be created in society to maintain it; they analyzed factors that ensure the sustainability of an economic system and its capability to withstand threats (Kharazishvili 2019, Varnaliy et al. 2016, Cable 1995, Wimbush, Tsereteli 2008, Yapatake et al. 2018). The application of a managerial approach to the analysis of these indicators allowed scientists to develop a mechanism of economic security at the meso-level (Chistnikova

et al. 2017), substantiate the institutional aspects of economic security and achieving sustainable economic development (Grigoreva, Garifova 2015), and identify the possibility of regional convergence on this basis to overcome the consequences of the economic crisis (Koudoumakis et al. 2019).

The authors' analysis of scientific achievements in this field shows that researchers have used various indicators that, from their point of view, characterize the economic security of the regions, and proposed various methodological approaches to its evaluation. In the process of analysis, the researchers used nationally approved methodological approaches and indicators to assess the level of economic security (Kharazishvili 2019), and proposed their own approaches to its analysis.

The generalization of the results of the analysis of previously published scientific works devoted to the assessment of the economic security of regions, allowed the authors to establish that these indicators include: the level and quality of life (Karpov et al. 2016); labor and non-labor incomes; the level of income differentiation (Duran 2015); employment and unemployment rates in the region (Kharazishvili 2019, Ovcharenko et al. 2021); the level of government and local government spending on public goods (Batabyal Amitrajeet 2018); domestic and foreign investment in the region (Novikova, Krasnikov 2010); consolidated index of innovative development of the region, which allows to identify areas (regions) with a critical, relatively stable, and medium level of economic security (Arkhipova, Kulikova 2020); socio-economic development (Ivanova 2018); indicators that characterize the environmental situation in the region (Tiutiunyk et al. 2017), and others. The weaknesses of the researchers' approaches are that they use metrics which are indicators of multiple components of economic security, only focus on assessing certain components of economic security and ignore others, and use too many metrics to evaluate.

That is why, at the present stage of the development of economic science, there has not been formed a single approach to the sample of metrics that would reflect the state of economic security. In our opinion, more objective results can only be obtained by generalizing the approaches of the researchers and by applying a systematic approach to the selection of metrics for assessing economic security.

On the other hand, scientists studied the methodology and principles of assessing the economic security of regions and compared the advantages and disadvantages of scientific approaches to its analysis (Granberg et al. 2008).

For instance, Onyshchenko, Bondarevska (2018) proposed to assess the economic security of regions based on monitoring and analyzing the key economic indicators and threats, by determining the threshold, critical, and acceptable values of the level of economic security and its components (Onyshchenko, Bondarevska 2018). The weak point of this method is that the threshold values of metrics are very difficult to determine, in particular, quantitative and critical parameters that would accurately reflect the approach of the metrics to a critical level and that would take into account the interests of the region.

Akberdina et al. (2017) substantiated the approach according to which an assessment of the economic security of the region is carried out based on analysis of production, social, environmental, financial, and innovation-investment indicators of the functioning of the sectors of the region, as well as the level of development of networking industries. The approach determines the level of economic security through the construction of a function that includes the above indicators, and time series characterizing changes in time of certain indicators (Akberdina et al. 2017). This approach requires processing too many metrics at the same time, which in our opinion complicates the analysis, since a large array of data is difficult to formalize and describe.

Chichkanov et al. (2020) applied a qualitative approach to assessing the economic security of a region by analyzing the factors influencing the development of industries in the region, such as historical, cultural, economic, and social factors, based on the method of expert estimates and further ranking of these factors (Chichkanov et al. 2020). However, in our opinion, the results obtained through the application of the expert assessment method are quite subjective and do not reflect a true picture of the region's development.

Chistnikova et al. (2017) proposed to assess economic security based on indicators of

threats, such as socio-demographic, economic, and investment threats, that exist in the region, and further on to identify the condition of the regional system as a normal, crisis, or critical one (Chistnikova et al. 2017). However, we believe that this approach only forms an idea of the negative factors that may affect the socio-economic development of the region, rather than assess the level of its economic security. Moreover, as a methodological basis, the researchers have chosen the threshold method that only answers the question of whether we have reached the threshold level or not, but does not allow for a quantitative assessment of the level of economic security.

Iefimova, Labartkava and Pashchenko assessed economic security through the method of normalized values and analysis of direct and reverse action factors, where the former contributes to an increase in the level of economic security, and the latter, reduces its level (Iefimova et al. 2020). The assessment was based on indicators of economic development and investment status of the regions, as well as demographic indicators. The weak point of this approach is that it does not consider such indicators as the income of regional entities, the level of their financial security, or the region's participation in foreign economic activity. Yet, it is these indicators that allow characterizing the level of security of each individual, enterprise, and region, to form an idea of the security of all participants in economic activity in the region.

Despite the achievements of the researchers in the field of methodology for assessing the economic security of regions, the proposed approaches have a number of weak points. This identifies the problem under study, i.e., the search for a more flexible, realistic, and therefore, more effective method of assessing the economic security of regions, which would avoid the above shortcomings.

The scientists have proven, and we agree, that economic-mathematical modeling is a productive methodological approach to assessing economic security (Cable 1995, Granberg et al. 2008, Kharazishvili 2019, Iefimova et al. 2020, Chichkanov et al. 2020, Onyshchenko, Bondarevska 2018). Thus, significant advances in assessing the level of economic security of regions were achieved by using the clustering method (Ivanova et al. 2020, 2021, Ovcharenko et al. 2021) and the nonlinear approach and the method of fuzzy logic, whose current methodological foundations were substantiated by Piegat (2001), Zelentsov, Korotka (2018). In view of this, the authors of this article in their previous research used the method of clustering to assess the economic security of regions. Based on the results obtained, we proposed an approach to identifying the cluster groups of regions as outsiders, leaders in the level of economic security, or having an average level of economic security (Ovcharenko et al. 2021). In our opinion, the previously obtained results can be enriched and become the basis for further research in this area, this time using the method of fuzzy logic.

For example, using the latter method, the researchers have proven that income differentiation produces a significant impact on the economic security of regions and on their labor potential (Duran 2015, Harmider et al. 2019), developed a methodology for integral analysis of the level of security of sustainable development in Ukraine (Kharazishvili 2019), built a model of an economic security management system (Feofilova et al. 2015), formed a model of sustainable development of the national economy due to an increase in the level of economic security (Nilashi et al. 2018), analyzed the conditions of uncertainty and their impact on the economic security of the country (Guseva et al. 2017), and the possibility of potential economic situations in these conditions (Voynarenko et al. 2021). However, scientists have not assessed the level of economic security using the fuzzy logic method. Therefore, the novelty of this article is the application of a new methodological approach to assessing economic security – fuzzy modeling.

The fuzzy modeling method has significant advantages over deterministic approaches in assessing the economic security of regions. First, this method allows fuzzy input data to be used in simulation and formalized through the mathematical apparatus of fuzzy set theory (Piegat 2001). In addition, fuzzy inference makes it possible to obtain output data that can be reduced to clear values using defuzzification methods.

The fuzzy logic method, compared to other methods, opens up opportunities to obtain fuzzy models that are closer to the real processes they describe, as well as more accurate and objective results in the process of assessing the level of economic security.

Table 1: Stages of assessing the level of economic security of regions

Stage	Description
1	Formation of a set of indicators that characterize the economic security of the region, their distribution by groups (input data of the system)
2	Formalization of fuzzy data using linguistic variables
3	Construction of a fuzzy rule base: description of linguistic variables using membership functions; formation of the rule base; determination of the required number of rules for an adequate description of the model; the choice of the defuzzification method for obtaining the value of the integral index of the economic security of a region (the output variable of the system)

Source: authors approach

This, in turn, is the basis for the formation of effective approaches to decision-making and economic security management by public authorities and local governments at the meso-level of the economy. Therefore, we consider the method of fuzzy logic to be the most promising for scientific analysis.

The purpose of the article is to form methodological tools for assessing the economic security of regions based on the method of fuzzy modeling, and to develop approaches for managing the economic security of a region by public authorities and local governments.

3 Data and methods

The fuzzy logic approach is proposed to assess the economic security of the regions. The application of the mathematical apparatus of fuzzy set theory (fuzzy logic, fuzzy inference, fuzzy modeling, etc.) allows solving problems, whose solution by traditional methods is ineffective or completely impossible due to limited information about the system or object of research (Piegat 2001). These systems operate under conditions of uncertainty, but describe the object of modeling more closely to the real one and require the use of fuzzy economic and mathematical models.

Given that the assessment of economic security of regions is based on the analysis of factors that affect it and which are often unclear and need to be formalized, in our opinion, the use of traditional approaches is not appropriate here. That is why, to assess the economic security of regions, we propose a methodological approach which is based on the fuzzy logic method and allows the research in statics and dynamics, analysis of quantitative and qualitative indicators, assessment of the overall level of economic security and of its individual components, and taking effective managerial decisions.

The algorithm for assessing the level of economic security of regions includes three stages (Table 1).

At the first stage, a set of indicators of economic security of a region is formed to be further used for the construction of an integral index as a basis for assessing the level of economic security.

The analysis of scientific publications on this issue, carried out by the authors, made it possible to establish that the major components of economic security of a region are the investment, innovation, financial, foreign trade, demographic, social security, and security of economic activity (Sukhorukov, Kharazishvili 2012, Denezhkina, Suzdaleva 2011, Chistnikova et al. 2017, Akberdina et al. 2017, and other authors). Based on the results of these studies, the authors of the article have worked out a set of indicators that characterize the economic security of the region, as well as its components. These indicators are further used by the authors to build an integral index as a basis for assessing the level of economic security (stage 1).

The indicators for assessing the components of economic security of the regions and their limiting values are presented by the authors in Tables 2 and 3. The limit values for the indicators in Table 3 are indicated according to the results of the studies and previous recommendations of the scientists (Sukhorukov, Kharazishvili 2012, Kalina, Savelyeva 2014, Karpov et al. 2016, Novikova, Krasnikov 2010, Illarionov 1998, Denezhkina, Suzdaleva

2011, Karpov, Korablevoy 2017, Makhanko et al. 2017, Ferova, Krot 2016, Kharazishvili, Liashenko 2019).

Table 2: Indicators (aggregated influencing factors) for assessing the economic security of a region

Name of indicator	symbol
Investment security	X_1
Innovation security	X_2
Financial security	X_3
Foreign trade security	X_4
Social security	X_5
Demographic security	X_6
Security of economic activity	X_7

Source: authors' approach

Table 3: Indicators (specific factors) for assessing the economic security of a region

Name of Indicator	Symbol	Limit value
Capital investment to GRP ratio for the relevant period	x_1	$25-30$
Indicator of innovation activity	x_2	≥ 2
Indicator of the region's financial security	x_3	≥ 50
Indicator of the region's exports to imports ratio	x_4	$2-5$
Share of imports in GRP	x_5	≥ 0.3
Unemployment rate	x_6	≥ 4
Share of the population with incomes below the subsistence level	x_7	≥ 7
Overall crime rate	x_8	≥ 0.016
Population income level	x_9	$5-6$
Depopulation rate	x_{10}	> 1
Population reproduction rate	x_{11}	> 2.3
Industrial production index	x_{12}	> 105
Agricultural production index	x_{13}	> 105
GRP volume ratio	x_{14}	$> 103-104$
GRP per capita by region to GRP per capita by country ratio	x_{15}	> 100
Level of the region's economy shadowing	x_{16}	< 50

Source: authors' approach

Investment security is a state of the investments being protected from internal and external threats, which allows preventing a decrease in their volume in conditions of an acceptable level of risk (Bobrovska et al. 2021). The share of capital investments in Gross Regional Product (GRP) is used to assess investment security. The level of investment security should be such as to ensure the growth of production of tangible and intangible goods in accordance with market needs and an efficient use of investment resources in the region, considering its natural, economic, socio-demographic, as well as scientific and technological factors (Hordiienko, Boiarko 2013).

The security of innovative development is determined by the region's capabilities for the production and introduction of innovations in all spheres of management, as well as for maintaining and developing its scientific and technical potential (Arkhipova, Kulikova 2020). To analyze the innovation component, the indicator of innovation activity is used, which is calculated as the ratio of scientific and technological development financing from all financing sources to GRP.

The financial security of the region is characterized by the capability to meet the region's needs with the revenues received and by the degree of dependence of the regional budget on the state one. The coefficient of the region's financial security is used for its assessment. This indicator is measured as the ratio of the amount of reverse subsidies to the regional budget to the amount of basic subsidies to the regional budget (Ovcharenko et al. 2021). Reverse subsidies are funds that the region transfers to the state budget

for the horizontal equalization of the tax potential of the territories. Basic subsidies are financial resources that are allocated from the general fund of the state budget to increase the fiscal capacity of local budgets (Ovcharenko et al. 2021). Basic subsidies cover the regional expenditures, primarily with tax revenues, which the local budget cannot provide at the expense of its own revenues.

The foreign trade security of the region shows the degree of openness of the region's economy, the capability of the regional enterprises to produce and sell competitive products in the international market (Grigoreva, Garifova 2015). This contributes to the socio-economic development of the region and raising the living standards of its population. The foreign trade security of the region is assessed using, first, the region's exports to imports ratio.

Social security is a component of economic security and is at the intersection of interests of an individual and the region (Karpov, Korablevoy 2017). This indicator characterizes the level of the population income, social instability and social unrest in the region, social attitudes and behaviour of the region's population, and includes the following indicators: unemployment rate, the share of the population with incomes below the subsistence level, the total crime rate, and the population income level – per capita income to the subsistence level ratio.

Demographic security characterizes the level of provision of the region with labor resources which is the most important type of economic resources and creates the basis for its economic development (Kharazishvili 2019, Ovcharenko et al. 2021). This indicator is formed, firstly, based on the depopulation rate, i.e., the ratio of the number of births to the number of deaths over a period, and secondly, the reproduction rate, i.e., the ratio of the number of children born per year to the average annual number of women in the region.

Security of economic activity in the region reflects the general state of socioeconomic development of the region (Sukhorukov, Kharazishvili 2012) and is characterized by the following indices: industrial production index, agricultural production index, GRP volume ratio, and the ratio of the region's GRP per capita to the country's GRP per capita. The latter index reflects the state of region's development relative to other regions in Ukraine, and characterizes the level of the economy shadowing.

Indicators $x_1, \dots x_{16}$ (private factors) were taken from the national (regional) statistical database. For the calculation of indicators of investment, innovation, financial, foreign trade, social, demographic security, and the safety of economic activity ($X_1, \dots X_7$), the fuzzy rule base was used, which was compiled according to the methodological approach described below by the authors.

In this article, statistical data from the regions of Ukraine, which have been calculated by the State Statistics Service of Ukraine, are used as input data for assessing the economic security of the region. To demonstrate the practical application of the proposed methodological approach, 2017 data from 10 of the 24 regions in Ukraine have been analyzed (in Ukraine, statistical information on regions is generated with a significant delay). In particular, R_1 – Vinnytsia region, R_2 – Dnipropetrovsk region, R_3 – Zhytomyr region, R_4 – Zaporizhia region, R_5 – Kyiv region, R_6 – Lviv region, R_7 – Odessa region, R_8 – Poltava region, R_9 – Kharkiv region, R_{10} – Chernihiv region. The input data used to analyze these regions are shown in the Table 4.

Analysis of the methodology for calculating the indicators selected by the authors for the study (Table 4) showed that in terms of statistics, these indicators are of fuzzy, blurred, or interval nature, as they fluctuate within certain limits. For example, the methodology for calculating the industrial production index is based on the use of data on changes in the production of certain types of industrial products (set of industrial goods) in the dynamics using the appropriate individual indices for each product. Accordingly, this indicator can be set by interval values. Thus, it is obvious that the other indicators selected by the authors for the analysis are vague and cannot be considered as point values. In this case, for modeling it is necessary to choose mathematical methods that can be used to analyze fuzzy sets, i.e., quantities that can vary within certain limits and which are not point, but fuzzy quantities. Therefore, when solving this class of problems, it is advisable to abandon the use of deterministic approaches and methods, because they

Table 4: Input data for assessing the economic security of regions

	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8	R_9	R_{10}
x_1	12.66	13.67	12.53	12.20	21.97	16.35	14.91	10.54	10.35	13.06
x_2	0.05	0.71	0.05	0.66	0.18	0.23	0.18	0.04	1.16	0.08
x_3	0.28	9.8	0.24	2.38	7.15	0.53	0.8	5.09	1.28	0.2
x_4	2.99	1.53	1.31	2.24	0.51	0.73	1.27	1.62	0.74	1.40
x_5	0.12	0.40	0.20	0.28	0.59	0.40	0.26	0.21	0.23	0.21
x_6	10.7	8.5	10.8	10.7	6.5	7.5	7.3	12	6.1	11.2
x_7	7.7	6.9	18.1	4.9	7.4	6.2	4.0	2.2	4.5	7.4
x_8	0.009	0.014	0.012	0.019	0.015	0.011	0.014	0.016	0.013	0.015
x_9	2.1	2.7	2.0	2.6	2.5	2.2	2.4	2.3	2.3	2.0
x_{10}	0.59	0.54	0.58	0.51	0.61	0.78	0.76	0.47	0.53	0.40
x_{11}	0.02	0.02	0.02	0.01	0.02	0.02	0.02	0.01	0.02	0.01
x_{12}	108	100	110	106	110	106	112	99	106	97
x_{13}	96	101	106	97	96	106	99	83	90	105
x_{14}	103	103	103	105	105	102	107	96	100	100
x_{15}	0.92	1.54	0.79	1.19	0.92	1.43	0.99	1.68	1.10	0.87
x_{16}	44.9	44.3	50.2	44.3	50.2	43.5	44.3	44.9	44.3	50.2

Source: State Statistics Service of Ukraine (Derzhavna sluzhba statystyky Ukrainy)

will not fully describe the process being modeled. In this case, we must work with fuzzy economic models (Diligenskij et al. 2004), which require methods of the mathematical apparatus of fuzzy set theory. Fuzzy modeling involves working with fuzzy quantities and their membership functions (Piegat 2001, Shtovba 2009, Zelentsov, Korotka 2018). The application of this method will allow working with fuzzy or blurred data, to perform simulation which is closest to the real described systems, and to avoid the shortcomings of deterministic approaches. That is why we consider the method of fuzzy modeling the most acceptable for the analysis of the output data of this kind.

In this study, fuzzy information is formalized through fuzzification operations. Mamdani-algorithm is used for fuzzy inference, which is based on the fuzzy knowledge base built in the work (Zheng-Hua 2006, Piegat 2001, Zelentsov, Korotka 2018, Harmider et al. 2019). The process of its implementation is described below.

Since the input factors are blurred, the output data on the assessment of the level of economic security of the region will also be characterized by fuzziness. Therefore, it is necessary to formalize all the information about the input and output data using the mathematical apparatus of fuzzy logic (second stage).

The output variable – the integral index of economic security of the region (I_b) – is calculated based on the values of the input indicators as (1):

$$I_b = R(X_1, X_2, X_3, X_4, X_5, X_6, X_7) \tag{1}$$

where I_b is a functional for assessing the economic security of the region, which depends on seven functions. On (2):

$$X_i = r_i(\bar{x}) \tag{2}$$

where X_i are aggregated influencing factors (in the graphical representation: the arcs of the graph, which come from non-terminal vertices) ($i = 1, \dots 7$); $r_i(\bar{x})$ are convolutions of factors; $\bar{x}$ are vectors of specific factors. The variables x_j are given in Table 3.

The above functions of the convolution of factors have the form: $X_1 = r_1(x_1)$ – investment security; $X_2 = r_2(x_2)$ – innovation security; $X_3 = r_3(x_3)$ – financial security; $X_4 = r_4(x_4, x_5)$ – foreign trade security; $X_5 = r_5(x_6, x_7, x_8, x_9)$ – social security; $X_6 = r_6(x_{10}, x_{11})$ – demographic security; $X_7 = r_7(x_{12}, x_{13}, x_{14}, x_{15}, x_{16})$ – security of economic activity.

Variables $x_j = [x_j^-; x_j^+]$, $j = 1, \dots 16$ are fuzzy values. Each of them varies in its respective range $[x_i^-; x_i^+]$. Obviously, the influential factors X_i will also be fuzzy sets, whose ranges of definition depend on specific factors. The functions r_i have no analytical task ($i = 1, \dots 7$), but it is possible to use expert estimates to construct them.

Formally fuzzy mathematical model for assessing the economic security of the region can be represented as (3):

$$\left.\begin{array}{l} X_1 = \{[x_1^-; x_1^+]\} \xrightarrow{r_1} \tilde{X}_1 \\ X_2 = \{[x_2^-; x_2^+]\} \xrightarrow{r_2} \tilde{X}_2 \\ X_3 = \{[x_3^-; x_3^+]\} \xrightarrow{r_3} \tilde{X}_3 \\ X_4 = \{[x_4^-; x_4^+]; [x_5^-; x_5^+]\} \xrightarrow{r_4} \tilde{X}_4 \\ X_5 = \{[x_6^-; x_6^+]; [x_7^-; x_7^+]; [x_8^-; x_8^+]; [x_9^-; x_9^+];\} \xrightarrow{r_5} \tilde{X}_5 \\ X_6 = \{[x_{10}^-; x_{10}^+]; [x_{111}^-; x_{11}^+]\} \xrightarrow{r_6} \tilde{X}_6 \\ X_7 = \{[x_{12}^-; x_{12}^+]; [x_{13}^-; x_{13}^+]; [x_{14}^-; x_{14}^+]; [x_{15}^-; x_{15}^+]; [x_{16}^-; x_{16}^+];\} \xrightarrow{r_7} \tilde{X}_7 \end{array}\right\} \xrightarrow{R} \tilde{I}, \quad (3)$$

where X_j $j = 1, \ldots 7$ are input fuzzy vectors of groups of coefficients; r_i are unknown laws that transform fuzzy sets of input vectors into sets of groups of fuzzy indicators ($\tilde{X}_j$); R is an unknown law that transforms sets of groups of fuzzy indicators into a fuzzy set for assessing the economic security of the region $\tilde{I}$.

At the third stage, it is necessary to quantitatively reproduce linguistic variables and their membership functions. To do this, we build a fuzzy knowledge base considering direct expert estimates, and choose an algorithm for fuzzy inference (Zheng-Hua 2006, Piegat 2001). After that, we carry on as follows: select the operation of blurring (fuzzification) of fuzzy sets; construct a fuzzy knowledge base that satisfies the conditions of completeness and / or linguistic and / or numerical completeness; select the relevant operation of fuzzy inference; select operations of defuzzification to reduce the variables, which have been received as a result of fuzzy derivation, into a crisp set; obtain the value of the membership function for a crisp result for the economic security of the region.

Since limits of variation of input data are known, it is proposed to formalize the fuzzy information about them using membership functions (MF). It is known that there are indirect (using statistics, pairwise comparisons, rankings, etc.) and direct approaches to their construction. When choosing a method, one should consider the difficulty obtaining expert information, its reliability, and the complexity of the algorithm for processing the information. The use of the direct method using expert data is relevant, since this method significantly reduces computational costs (Shtovba 2009, Piegat 2001). The number of term sets for the description of linguistic variables is also given, considering direct expert estimates.

In order to assess the linguistic indicators that characterize the economic security of the region, the authors propose the following scale for evaluation of indicators and their subsequent classification for the input data: C – crisis level; L – low level; M – medium level; AM – above medium level; H – high level.

Based on this, the following scale is used to assess the possible values of the output variable I_b: CS – crisis level of economic security of the region; LS – low level of economic security of the region; MS – the medium level of economic security of the region; AMS – above medium level of economic security of the region; HS – a high level of economic security of the region. Table 5 shows the quantitative characteristics of the limits of the terms of linguistic variables proposed by the authors.

To adequately describe the object of modeling, it is necessary to decide on a sufficient number of logical rules of a fuzzy knowledge base (FKB) (Zheng-Hua 2006, Piegat 2001). The quality of the fuzzy rule base (RB) determines how fully and adequately the modeling process will be carried out. When constructing the FKB, we take into account that: the properties of the rules can be of a local nature; the total number of rules is important; completeness of the model is important; consistency of the rule base, and RB connectivity are important.

If we leave five terms for each private variable x_1, $(i = 1, \ldots 16)$, it is obviously quite difficult (in fact impossible) to describe a fuzzy base $5^{16} = 1.5259 * 10^{11}$ and add terms for the output variable I_b. The situation looks much better when there is a grouping of factors (i.e., some hierarchy of rules), and the functional I_b is considered from a mathematical point of view. This will significantly reduce the number of rules, which can range from 72 to 75.

Table 5: Limits of terms for linguistic variables

	Input data				
	C	L	M	AM	H
X_1	0-12	8-21	18-32	28-42	38-50
X_2	0-3	1-5	3-9	7-16	14-25
X_3	0-0.58	0.42-0.83	0.67-1.08	1.17-1.58	1.42-2.0
X_4	0-1.2	0.8-2.3	1.8-3.2	2.8-4.2	3.8-5
X_5	0-2.2	1.6-4.7	3.8-6.2	5.8-8.2	7.8-10
X_6	0-2.2	1.6-4.7	3.8-6.2	5.8-8.2	7.8-10
X_7	0-55	45-105	100-125	115-165	160-200
	Output variable				
	CS	LS	MS	AMS	HS
Ib	0-2.2	1.8-4.2	3.8-6.2	5.8-8.2	7.8-10

Source: authors' approach

Table 6: Fragment of the fuzzy inference system for indicators

IF (x_4 = H & x_5 = M),	THEN X_4 = H
IF (x_6 = M & x_7 = H & x_8 = H & x_9 = M),	THEN X_5 = H
IF (x_{10} = M & x_{11} = M),	THEN X_6 = M
IF (x_{12} = M & x_{13} = H & x_{14} = H & x_{15} = H & x_{16} = AM),	THEN X_7 = H
IF (x_1 = H & x_2 = H & x_3 = H & X_4 = H & X_5 = H & X_6 = H & X_7 = H),	THEN R = AMS

The authors propose to consider not a linguistically complete but a numerically complete base of rules, when each crisp input state $(X_1^*, X_2^*, X_3^*, X_4^*, X_5^*, X_6^*, X_7^*)$ corresponds to the activation of at least one rule R^*. The latter approach allows a further reduction in the size of the rule base and adequate description of the modeled object.

The knowledge base was configured using expert a priori knowledge. For some variables, the number of terms has been reduced; various membership functions (trapezoidal or bell-shaped) and their parameters were selected.

Given that RB has about 100 rules, it is possible to make a mistake in their formation. The measurement of input and output data of the system was checked for unambiguity, when one input state $(X_1^*, X_2^*, X_3^*, X_4^*, X_5^*, X_6^*, X_7^*)$ can correspond to different output values of economic security of the region. The rules were tested for incompatibility and any of such happenings were excluded.

Mamdani-type inference was used as a fuzzy inference algorithm. To formalize fuzzy input information, membership functions of different types were used depending on expert estimates and the problem to be solved.

As a result, the fragment of the fuzzy inference system for indicators (private factors) that characterize the aggregated influencing factors (shown in Table 3) has the form shown in Table 6.

In fact, we have a hierarchical system of fuzzy inference, and accordingly, it is necessary to write a fuzzy knowledge base for aggregated factors, a fragment of which is given in Table 7.

Since the Mamdani fuzzy inference algorithm has been chosen, the logical minimum operation is taken as the implication, and the logical maximum operation is taken as the composition operation (Piegat 2001, Zelentsov, Korotka 2018, Korotka 2021). To obtain a crisp value from a fuzzy set, the centroid method (4) was used:

$$\mu(r) = \frac{\int_{\underline{u}}^{\overline{u}} u\mu_\Sigma(u)du}{\int_{\underline{u}}^{\overline{u}} \mu_\Sigma(u)du} \tag{4}$$

where μ_Σ is the membership function of the obtained fuzzy set as a result of implication

Table 7: Fragment of a fuzzy knowledge base for aggregated factors

Rule(1):	IF X_1="L" and X_2="C" and X_3="C" and X_4="M" and X_5="L" and X_6="C" and X_7="L",	THEN y="LS"
Rule(2):	IF X_1="L" and X_2="C" and X_3="C" and X_4="L" and X_5="C" and X_6="C" and X_7="C",	THEN y="CS"
Rule(3):	IF X_1="L" and X_2="C" and X_3="H" and X_4="L" and X_5="L" and X_6="C" and X_7="M",	THEN y="LS"
Rule(4):	IF X_1="AM" and X_2="AM" and X_3="AM" and X_4="AM" and X_5="AM" and X_6="AM" and X_7="AM",	THEN y="AMS"
Rule(5):	IF X_1="AM" and X_2="AM" and X_3="H" and X_4="H" and X_5="H" and X_6="H" and X_7="H",	THEN y="HS"
Rule(6):	IF X_1="H" and X_2="H" and X_3="H" and X_4="H" and X_5="H" and X_6="H" and X_7="M",	THEN y="HS"
Rule(7):	IF X_1="H" and X_2="H" and X_3="H" and X_4="H" and X_5="H" and X_6="M" and X_7="M",	THEN y="AMS"
Rule(8):	IF X_1="H" and X_2="H" and X_3="H" and X_4="M" and X_5="M" and X_6="M" and X_7="M",	THEN y="MS"
Rule(9):	IF X_1="H" and X_2="H" and X_3="M" and X_4="M" and X_5="M" and X_6="M" and X_7="M",	THEN y="MS"
...	...	...

and composition operations; $\underline{u}$ and $\overline{u}$ are, respectively, the left and right boundaries of this fuzzy set.

Software developed by one of the authors of this article (Korotka 2021) was used for fuzzy modeling and conducting numerical experiments with simulation models. The software implements the Mamdani fuzzy inference algorithm. The C++ programming language and the Visual Studio Community development environment were used (Korotka 2021).

4 Results and Analysis

The proposed methodological approach was used to assess the level of economic security of the regions in Ukraine. Table 8 presents the values of the output variables and the results of modeling the system for the selected ten regions.

The obtained results assert that the fuzzy information has been formalized, and the constructed knowledge base adequately describes the modeled process. The values of membership functions are close to 1 in almost all the experiments, which indicates a sufficient number of values of the linguistic variable of the functional for assessing the economic security of the region.

Graphical interpretation of the results of the study is presented in Figures 1 and 2. The results of the calculations show that the integral indices of economic security (I_b) correspond to the terms LS and CS, and thus to low (in regions R_1, R_2, R_4, R_5, R_6, R_7, R_8, R_9, R_{10}) and crisis (R_3) levels of economic security of the regions. The lowest indicators of I_b are in Zhytomyr (I_b R_3 = 1.8), Vinnytsia (I_b R_1 = 2.15) and Lviv (I_b R_6 = 2.56) regions (Table 8, Figure 1). Among the 10 regions of Ukraine under study, there are no regions that correspond to high and medium levels of economic security (Table 8, Figure 1). The results of calculations show that the obtained integral indices of economic security of the regions are low, though with varying degrees of differentiation: Dnipropetrovsk region – 3.6; Odessa region – 3.43; Chernihiv region 3.39.

The results of the analysis of the regions' economic security by its components (X_1, X_2, X_3, X_4, X_5, X_6, X_7) indicate that in all the regions under consideration, demographic security (X_6) is at a crisis level (Table 8, Figure 2). This situation is because Ukraine has a high level of depopulation (x_{10}) and a low level of labor reproduction (x_{11}). The population does not receive enough income to reproduce the labor force and new generations, the number of women of childbearing age is decreasing, and the mortality rate exceeds the birth rate. In addition, there is a tendency of outflow of labor abroad and declining birth rates.

Table 8: Results of economic security assessment

	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8	R_9	R_{10}
					Input data					
X_1	L	L	L	L	M	L	L	C	C	L
X_1	(13)	(14)	(13)	(12)	(22)	(16)	(15)	(11)	(10)	(13)
X_2	C	C	C	C	C	C	C	C	C	C
X_2	(0.05)	(0.72)	(0.05)	(0.66)	(0.18)	(0.23)	(0.18)	(0.04)	(1.16)	(0.08)
X_3	C	H	C	H	H	L	M	H	H	C
X_3	(0.28)	(2.0)	(0.24)	(2.0)	(2.00)	(0.53)	(0.80)	(2.00)	(2.0)	(0.20)
X_4	M	L	L	L	C	C	L	L	L	L
X_4	(2.6)	(1.53)	(1.3)	(2.1)	(0.9)	(1)	(1.28)	(1.4)	(2.2)	(1.4)
X_5	L	L	C	L	L	L	L	M	M	L
X_5	(2.2)	(2.7)	(1.9)	(3.7)	(2.6)	(2.6)	(2.7)	(4.1)	(4.3)	(2)
X_6	C	C	C	C	C	C	C	C	C	C
X_6	(0.6)	(0.54)	(0.58)	(0.51)	(0.61)	(0.78)	(0.76)	(0.47)	(0.53)	(0.4)
X_7	M	M	L	M	M	M	M	M	M	M
X_7	(100)	(105.1)	(87.2)	(108.4)	(106.2)	(110.1)	(106.6)	(105.1)	(107.3)	(99.7)
					Defuzzificated value (output variable):					
I_b	LS	LS	CS	LS	LS	LS	LS	LS	LS	LS
I_b	(2.15)	(3.6)	(1.8)	(3.84)	(3.66)	(2.56)	(3.43)	(3.55)	(3.69)	(3.39)

Source: authors' calculations

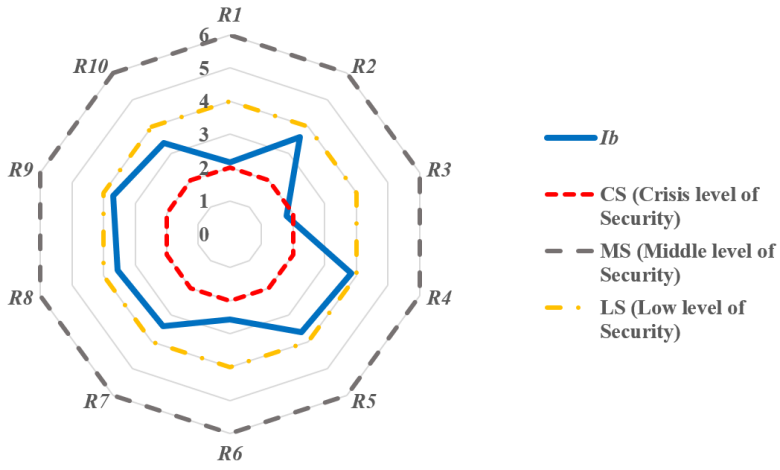
In our opinion, these negative tendencies directly affect the security of the social sphere of the regions (X_5). In the regions under study, there is a high level of unemployment (x_6) and crime (x_8), low income (x_9), and a high share of the population with income below the subsistence level (x_7). Only regions R_8 and R_9 show an average level of social security.

Furthermore, a similar situation is typical for indicator X_2: all regions, without exception, are characterized by a crisis level of innovation security (Table 8, Figure 2). In our opinion, this trend is due to low (in R_1, R_2, R_3, R_4) and crisis (in R_6, R_7, R_8, R_9, R_{10}) levels of investment security (X_1) in these regions. It was our analysis that showed that these regions are characterized by a low level of investment, which is associated with high risks for investing in Ukraine's economy under the economic and political crisis, unfavorable institutional conditions, and unstable regulatory framework in the field of investment and taxation. This causes low investment attractiveness of the regions and directly affects the level of innovation, which is insufficient to ensure the production of science-intensive and competitive products and modernization of fixed assets, as well as ensuring the proper functioning of enterprises in the regions.

Most regions are characterized by a high (R_2, R_4, R_5, R_8, R_9) and medium (R_7) level of financial security (X_3). Only the regions R_1, R_3, R_{10} show the crisis level of this indicator (Table 8, Figure 2). At the same time, there is a significant gap between the regions in terms of financial security. For example, the gap in x_3 is 10 times between Dnipropetrovsk and Chernihiv regions. This is due to the underdeveloped industrial potential in the regions R_{10}, R_1, R_3, R_7. Dnipropetrovsk region is the leader in terms of financial security (x_3), and Chernihiv region – an outsider in this regard.

At the same time, for all regions, except R_3, the level of economic security (X_7) is at the average level (Table 8, Figure 2). This tendency is due to the low level of x_{15} and the high level of x_{16} indicators in the R_3 region. In general, for the regions under study, the indicators of the industrial production index (x_{12}), the coefficient of GRP physical volume (x_{13}), and the ratio of per capita GRP by region to per capita GRP by country (x_{13}) correspond to the term M.

On the other hand, the studied regions are characterized by crisis (for R_5 and R_6) and low (for R_2, R_3, R_4, R_7, R_8, R_9, R_{10}) indicators of foreign trade security (X_4) (Table 8, Figure 2). The high level of the ratio of exports to imports (x_4), the share of imports in GRP (x_5) cause significant import dependence and negatively affect the level of economic



Source: authors' calculations

Figure 1: The level of economic security of the regions of Ukraine

security (X_7). This situation is associated with unfavorable economic and institutional conditions for economic activity in the regions, and low competitiveness of enterprises in the regions. This leads to a decrease in the industrial potential of the regions, reducing the share of small and medium-sized businesses, and insufficient level of development of the service sector and others. This contributes to the increase of x_5 and, accordingly, the import dependence of the regions, and, consequently, to the reduction of the level of foreign trade security of the regions.

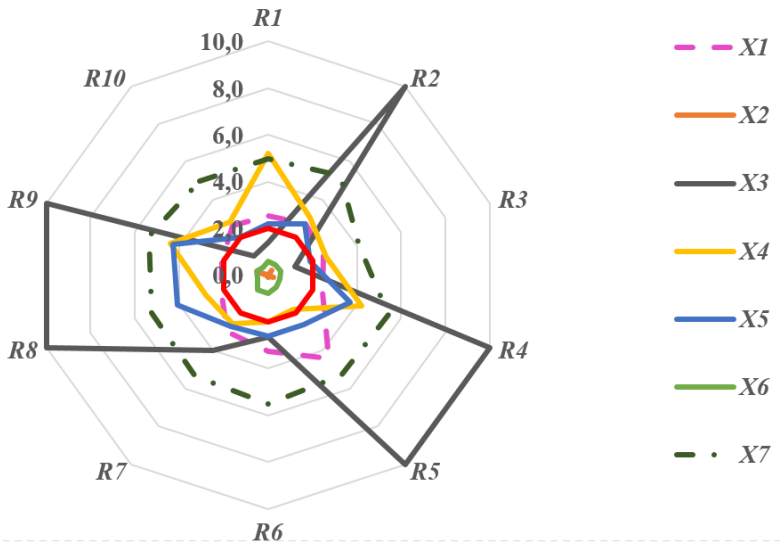
5 Conclusions

The results of numerical experiments allow us to draw the following conclusions. Firstly, fuzzy modeling is a powerful tool for describing complex nonlinear economic processes, such as the level of economic security. Secondly, this method makes it possible to operate with fuzzy / incomplete / blurred data which are difficult to formalize and which cannot be applied in accurate quantitative analysis and, as a result, their use is problematic in the implementation of deterministic approaches. Thirdly, the proposed fuzzy linguistic model of economic security describes the processes being modeled more transparently and closer to real situations.

The fuzzy model proposed by the authors is based on a Hierarchical Fuzzy Logic of Mamdani-type Fuzzy Inference System. This approach allows formalizing of all private factors and further working with aggregated influencing factors. In this work, a compact base of fuzzy rules has been formed, which is part of a numerically complete knowledge base.

The use of the level scale developed by the authors (Table 5), as well as the results obtained during the research, allowed the authors to conclude that the studied regions in Ukraine are characterized by uneven socio-economic development. According to this scale, these regions show high depopulation and unemployment, low investment and innovation activity, which has led to a critical state of demographic and innovation security in all regions, as well as low levels of investment and social protection in most regions. In addition, negative trends are observed in the area of foreign trade security. At the same time, five out of ten considered regions of Ukraine are characterized by a fairly high financial security.

The methodological approach proposed by the authors is quite flexible. However, a change in the number of input indicators, in our opinion, calls for the skills of a fuzzy system designer. During modeling, private indicators used in the formation of aggregated indicators can be redistributed by groups. This, however, will not significantly affect the process of obtaining the final results of the study, according to the authors, and will not reduce the significance of the proposed methodological approach.



Source: authors' calculations

Figure 2: Polygon of economic security of the regions of Ukraine

The results of the calculations indicate the need for taking managerial decisions by state and local governments in the regions that show crisis and low levels of economic security, and for measures to improve the situation. The capability of the region to ensure sustainable economic development, rational use of available economic resources, production of competitive goods, formation and use of innovation and investment opportunities, advance in research and technology, and maintaining the level and quality of life of the population lies not only in the plane of interests of the region itself, but also the interests of each person and society as a whole.

That is why economic security of each individual region and of the national economy as a whole will depend on the quality of managerial decisions at the level of state authorities and local self-governments. Given the current situation, in regions with crisis and low levels of investment, innovation, social, demographic, foreign trade, and economic security, there is a need to implement effective investment projects, which has to be done through public and private funding, introduce targeted programs of state support for these regions, form innovation clusters of regions to ensure the implementation of their economic potential, and create new workplaces and conditions for the development of services and entrepreneurship in these regions.

In addition, it is important to form a legal framework to support the development of the regions, which includes amendments to the legislation on decentralization, revision of the norms in the field of taxation and state regional policy, cooperation and association of territorial communities, delegation of powers to local governments, formation of effective models of financial support of the regions, and support of regional development.

This work is a contribution to the methodology of analysis and monitoring of economic security of regions, which consists of the application of a new methodological approach to its evaluation, namely, the method of fuzzy modeling. The use of the proposed approach will allow making more effective management decisions in the field of economic security of regions at the state and local government levels, identifying weaknesses and strengths of regions in the spheres of investment, innovation, financial, foreign economic, demographic, social security, and economic security. The results of the assessment of economic security of the regions in Ukraine, which were obtained by the authors, indicate the need for measures in the regions with crisis and low levels of economic security to reduce income shadowing, depopulation, unemployment, and crime, and to increase income and ensure its reproduction, stimulate investment, export orientation, and development of industrial production.

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